Aerodynamic Stability Considerations of High-Pressure Ratio, Variable-Geometry Jet Nozzles

J. S. ALFORD* AND R. P. TAYLOR†
General Electric Company, Cincinnati, Ohio

Descriptions are given for aerodynamic instability problems caused by 1) high area-ratio separation buffeting, 2) low area-ratio vibration, and 3) low-pressure ratio acoustic oscillations. These problems have been encountered in the development of high-performance air-breathing engines for operation at Mach 2.0 and above. Nozzle characteristics are inherently stable at design conditions. Self-excited instability has occurred at off-design conditions. Solutions that do not reduce performance are described for all of the types of instability. The variable-geometry converging-diverging jet nozzle has demonstrated outstanding reliability in approximately 230,000 flight hours as of March 1, 1964, accruing at a rate of approximately 10,000 hr/month.

Introduction

CONVERGING-DIVERGING jet nozzles provide high thrust by expanding engine exhaust gases efficiently. To maintain efficient expansion over a broad range of engine operating conditions, variable nozzle geometry is essential. Variable-geometry converging-diverging jet nozzles are inherently stable at design operating conditions, but at off-design conditions, self-excited aerodynamic instability has been observed.

Three types of aeroelastic instability have been encountered at General Electric in the development of high-pressure ratio, converging-diverging ejector-type jet nozzles. These are 1) buffeting at high nozzle area-ratios, 2) vibration at low area-ratios, and 3) oscillations at low operating pressure ratios. This paper briefly describes the observed instabilities and the solutions employed to eliminate each type.

High Area-Ratio Separation Buffeting

This type of instability can be understood best by a specific example. The problem was encountered on the J79-5 nozzle, commonly known as the "low base drag nozzle," which is used on the B-58. This nozzle consists of two basic and separate subcomponents, a converging portion and a diverging portion. Each is formed by twenty-four flaps hinged at the forward ends. Each set of flaps is supported and positioned by an actuation ring. Twenty-four seals riding on the flap surfaces complete the nozzle.

The converging portion of the nozzle is fully variable to satisfy the engine requirements. The diverging flaps have two positions, as shown in the schematic drawing and photographs in Figs. 1–3. The closed position of the secondary flaps is used for nonafterburning subsonic cruise operation, where a low area-ratio is desired for internal performance, and where the 15° boattail angle affords low afterbody drag. The open position is used for all of the afterburning conditions where a larger area-ratio nozzle is needed for supersonic flight speeds.

The high area-ratio separation buffeting was encountered in this nozzle in the open position at nozzle pressure ratios corresponding to low flight speeds, where the nozzle pressure ratio was not great enough for full expansion of the exhaust gases to the nozzle exit area. The gas flow must then separate from the divergent walls with a resultant shock wave. Figure 4 shows typical static pressure distributions along the nozzle diverging wall for three different conditions. The first condition, shown by the lower line x, is for a fully expanded nozzle with no flow separation within the nozzle and is inherently stable. The lines marked y and z show operation at lower nozzle pressure ratios where the flow expands to pressures substantially lower than ambient and then separates and shocks back to ambient pressure. This condition, coupled with the elastic characteristics of the nozzle flaps, created an aeroelastic instability.

The buffeting occurred at a nozzle pressure ratio of from 2.5 to 3.8 with a maximum double amplitude at the flap tips of about 1 in. Vibrational pickups installed on the nozzle flaps indicated a basic vibrational frequency of 9 to 12 cps superimposed on a pattern of much lower frequency and more random characteristics. Observations indicated that the diverging flap exit assumed an approximate elliptical shape that rotated slowly and randomly about the longitudinal axis of the engine.

It is interesting to note that this instability occurs at the condition where static nonelastic scale models showed a dual-valued expansion characteristic (hysteresis) with the thrust and pressure distributions dependent upon the direction from which the test point was approached.

On encountering the instability, a test program was initiated to develop an aerodynamic solution to the problem. It was reasoned that eliminating the source of the apparently large forces would provide a more satisfactory solution than designing to withstand them mechanically. The solution, which

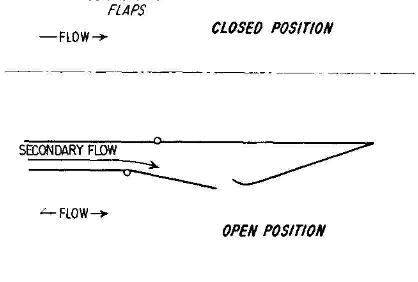

Fig. 1 Low base drag nozzle schematic.

Presented as Preprint 64-247 at the 1st AIAA Annual Meeting, Washington, D. C., June 29–July 2, 1964; revision received November 25, 1964. The authors gratefully acknowledge the valuable assistance given by H. P. Mehr, G. A. Pfefferkorn, J. M. Threlkeld, and other associates in the preparation of portions of this paper.

* Designing Engineer, Large Jet Engine Department.

† Aero-Thermo Engineer, Advanced Components Operation, Advanced Engine and Technology Department. Member AIAA.

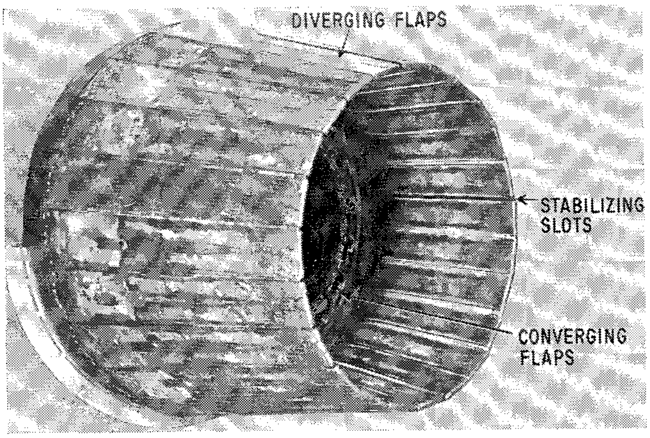

Fig. 2 Low base drag nozzle: closed position.

reduced the maximum vibrational amplitude at these conditions by 65% and eliminated entirely the elliptical tendency, was the provision of four axial slots in the diverging wall of the nozzle that opened to the cavity between the diverging wall and the outer or boattail wall. This cavity is an extension of the volume that supplies secondary cooling air to the nozzle. These slots are shown in the open-position photograph in Fig. 3. The total slot area used was 12.6% of the throat area of the converging nozzle at maximum afterburning, where the most severe vibration had occurred. When the diverging flaps are in the closed, or subsonic cruise condition, the diverging flaps are close together, and the slots are effectively eliminated.

The stabilizing functions of the slots are 1) to minimize the possible circumferential pressure gradient by venting at four locations to a common plenum chamber, thus reducing the elliptical tendency and 2) to allow a feedback of pressure from the stagnant high-pressure area behind the shock wave to the low-pressure area ahead of the separation, thus causing the flow to separate or to be stable in the axial position of its separation. It is interesting to note that the quantity of secondary air flow had little or no effect on the instability problem or on the stability solution.

Full-scale tests and detailed scale model tests indicate a very small effect on nozzle performance at design conditions (approximately $\frac{1}{10}$ of 1% loss) due to incorporation of the stabilizing slots.

These stabilizing slots initially were used on the J79-5 nozzle for developmental flight tests in 1958 and 1959 and have been incorporated into all of the operational B-58 aircraft. The mechanical integrity of the nozzle has proved to be outstanding. Approximately 230,000 hr of operational experience had been accumulated on this nozzle. The direct unscheduled maintenance for the nozzle has averaged less than 0.25 man hours/1000 flight hours. The reliability of the nozzle, as determined by flight power loss, flight engine shutdowns, or unscheduled engine removals, has been perfect (0 events). Because of this outstanding record, there are no regular maintenance or inspection intervals required.

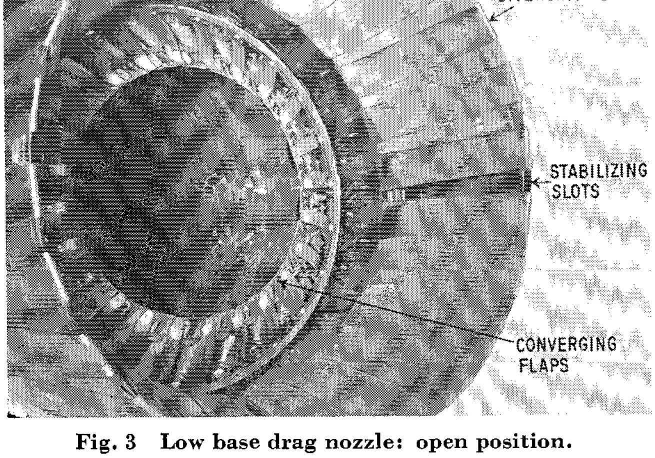

Fig. 3 Low base drag nozzle: open position.

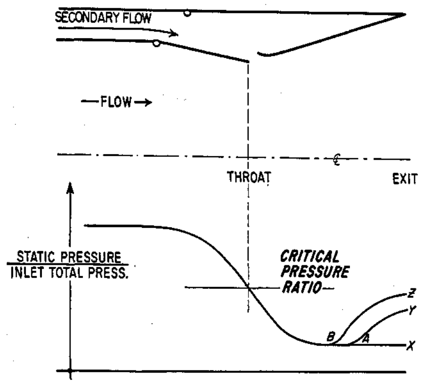

Fig. 4 Low base drag nozzle pressure distributions.

Low Area-Ratio Vibration

In a variable convergent-divergent exhaust nozzle designed for high performance, the condition sometimes exists where the area between the nozzle throat and the nozzle exit is greater than the nozzle exit, similar to the sketch in Fig. 5. With geometry like this, a number of different flow conditions exist during operation at different values of nozzle pressure ratios. Referring to Fig. 5, which shows the three distinct regions of the nozzle, the following different regimes of flow can exist.

Regime I: At low, subcritical nozzle pressure ratios 1) region 1 is a subsonic acceleration to a Mach number equal to or less than 1.0, 2) region 2 is a subsonic deceleration, and 3) region 3 is a subsonic acceleration to ambient pressure.

Regime II: At higher nozzle pressure ratios 1) region 1 is a subsonic acceleration to Mach 1.0, 2) region 2 is a supersonic acceleration, normal shock, and subsonic deceleration, and 3) region 3 is a subsonic acceleration to ambient pressure.

Regime III: At high nozzle pressure ratios 1) region 1 is a subsonic acceleration to Mach 1.0, 2) region 2 is a supersonic acceleration, and 3) region 3 is a supersonic deceleration to an exit Mach number greater than 1.0.

In actual operation of a nozzle, as pressure ratio is increased, the transition from regime I to regime II is a smooth, continuous change in nozzle wall pressures. However, transition from regime II to regime III can be unstable and transiently discontinuous, resulting in sudden changes in nozzle loading, which cause deflection of the nozzle structure leading to aeroelastic instability.

Two-dimensional tests were conducted, using transparent plastic model parts, which permitted the use of schlieren photos. Two of the schlieren are attached, and from Fig. 6, it can be seen that regime II operation is a normal shock

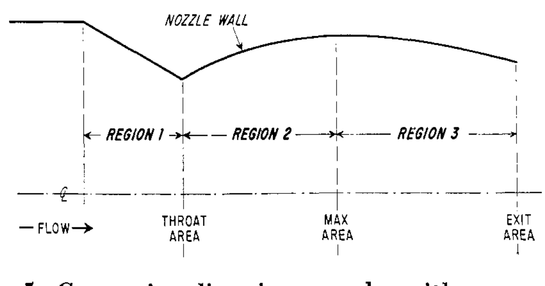

Fig. 5 Converging-diverging nozzle with supersonic convergence.

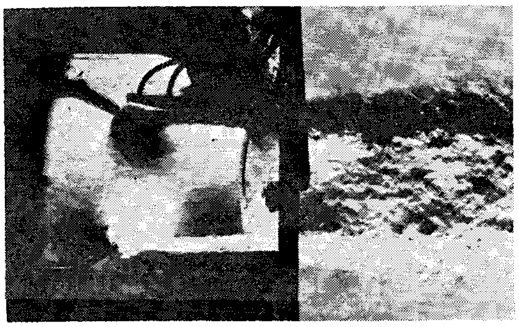

Fig. 6 Regime II operation.

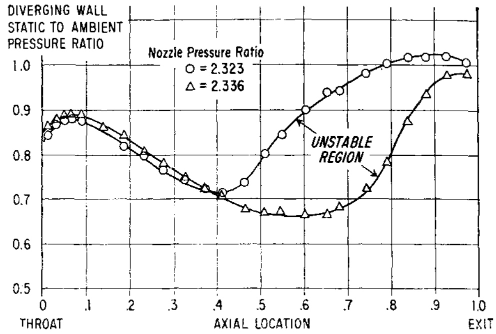

Fig. 8 Typical diverging wall pressures.

inside the nozzle. Increasing the nozzle pressure ratio slightly moved the normal shock out of the nozzle, giving regime III as shown in Fig. 7. This substantiates the findings on the three-dimensional model test, as shown in Fig. 8, in that it shows the rapid shock movements during transition from regime II to regime III that cause the aeroelastic instability. The schlieren also showed that the flow was attached during the shock movements (which is quite different from the J79-5 buffeting).

This low area-ratio instability has been encountered on two developmental exhaust nozzles. Three approaches to the problem have been evaluated. The first of these was to increase the area-ratio of the nozzle, thus eliminating the region of supersonic deceleration in the aft part of the nozzle. This solution has adverse performance effects and has not been utilized. The second solution was to increase the damping characteristics in the flaps and seals of the nozzle by the use of spring-loaded clips between the flaps and seals. This completely eliminated any instability and provided a good solution to the problem. The third solution was aerodynamic, as in the case of the J79-5 buffeting. It consisted of ventilation of the diverging walls of the nozzle to eliminate the instability. Initial attempts to solve the problem were to use the axial slots, which had been found effective in the case of the low base drag nozzle. This approach, however, was unsuccessful. It was then demonstrated that the vibration problem could be solved by either holes or a series of circumferential slots appropriately positioned in the diverging section of the nozzle. The holes presented an unacceptable performance loss, whereas the circumferential slots presented a very satisfactory solution in that the performance of the nozzle was unaffected by the change.

This instability problem causing high vibration was defined by static scale model tests. A series of $\frac{1}{8}$-scale, three-dimensional models was used to define the aerodynamic characteristics and evaluate potential solutions to the problem. The scale model test showed the rapid transition from the normal shock to the oblique shock (regime II to regime III), as described previously for the original unstable configuration. With the aerodynamic changes or ventilation, the scale model test revealed a gradual transition in the movement of the shock throughout the nozzle. This solution was then built into the full-scale variable hardware and provided an effective fix to the problem.

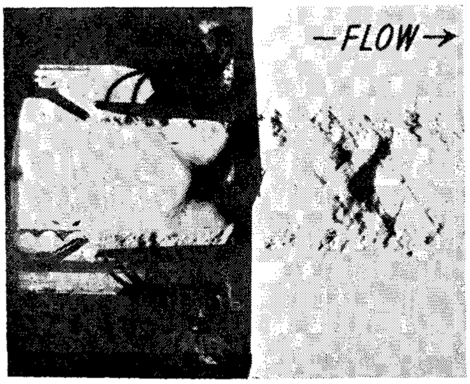

Fig. 7 Regime III operation.

Acoustic Oscillation with Subsonic Jet

The third type of instability mentioned at the beginning of this paper is low-frequency oscillations generated during operation with subsonic pressure ratio with overexpanded area-ratio. These relatively pure tones are recognized as acoustic oscillation of a coupled system comprised of tail pipe and jet nozzle. The source of instability is believed to be set by acoustic resonance in the tail pipe. The dynamic action appears to be similar to the modern conception of sound generation in organ pipes.

Investigation of one specific engine revealed that acoustic oscillations are generated at nozzle area-ratios above 1.35 with nozzle total pressure ratios between 1.08 and 1.6 (low engine speed at low flight speed). At normally scheduled area-ratios (1.38 to 1.55), oscillations are mild, and nozzle flap tip vibration levels were very low. At area-ratios above 1.55, intensity of oscillation increases rapidly, and sound pressure levels 30 decibels above the normal values have been measured, together with secondary nozzle flap tip vibrations in excess of 60 mils.

Acoustic oscillations are relatively pure single or double tones with frequencies between 90 and 150 cps and between 200 and 290 cps. In the lower frequency range, buzz frequency is a distinct function of nozzle pressure ratio and increases from 90 cps at 1.1 $P_{T8}P_0$ to 150 cps at 1.6 P_{T8}/P_0. In the upper frequency range, such a well-defined functional relationship does not exist. In most cases, the upper frequency is not a harmonic of the lower frequency. Static pressure measurements along the secondary nozzle inner wall indicate minimum wall pressure prior to the start of oscillation.

The nozzle area-ratio was found to be critical as regards generation of acoustic oscillations. Substantial oscillations were observed when the diverging walls were set to be relatively far open as compared to the nominal setting. With a properly vented nozzle, the acoustic oscillations are of low intensity if proper attention is paid to the selection and position of the exit area.

Conclusions

1) High-pressure ratio, converging-diverging jet nozzles are inherently stable at design operating conditions.

2) Self-excited aerodynamic instability has frequently occurred at off-design conditions, when the wall static pressures are substantially less than ambient.

3) Satisfactory solutions have been found and demonstrated

for every instability problem encountered. These solutions have not adversely affected performance and weight of nozzle.

4) The solutions are different. The fix for one type of instability will not necessarily be effective for a different configuration.

5) The existence of dual-valued expansion characteristics as a function of jet nozzle pressure ratio is one indication of potential instability.

6) The variable-geometry converging-diverging jet nozzle has demonstrated outstanding reliability in over 230,000 flight hours extended over about four years.

7) Available analyses of jet nozzle instability are inadequate. What is needed now is a quantitative analytical study of jet nozzles from the point of view of further classifying the types of instability that may be encountered and a program, which will make it possible to calculate such instabilities for any proposed design.